Metrology and Coatings for the 40 kg LIGO Optics

Rana X Adhikari
LIGO Laboratory
California Institute of Technology
Division of Physics, Math and Astronomy
1200 East California Boulevard, Pasadena, CA 91125, USA
rana@caltech.edu

Abstract: The 4 km LIGO interferometers seek to measure the gravitational radiation from cosmic explosions. In order to do so, their massive mirrors must meet several demanding specifications which are sometimes conflicting. I will described why the job is so challenging and how the challenges may be met.

OCIS codes: 120.0120, 000.2780

1. Introduction

The search for cosmic gravitational waves started in nearly 50 years ago and has enjoyed several enhancements over the years due to the tremendous leaps in the quality of lasers and optics. The imminent activation of a world wide network of kilometer scale laser interferometers is expected to open a new window onto the universe by allowing, for the first time, the observation of the bulk motions of massive stars, black holes, supernovae, pulsars, and perhaps a vast panoply of unexpected astrophysical and cosmological phenomena. The dark side of the universe is about to be revealed. In order to achieve astrophysically interesting strain sensitivities ($\simeq 10^{-21} - 10^{-23}$), these large laser interferometers require mirrors which push the limits of modern fabrication and metrology.

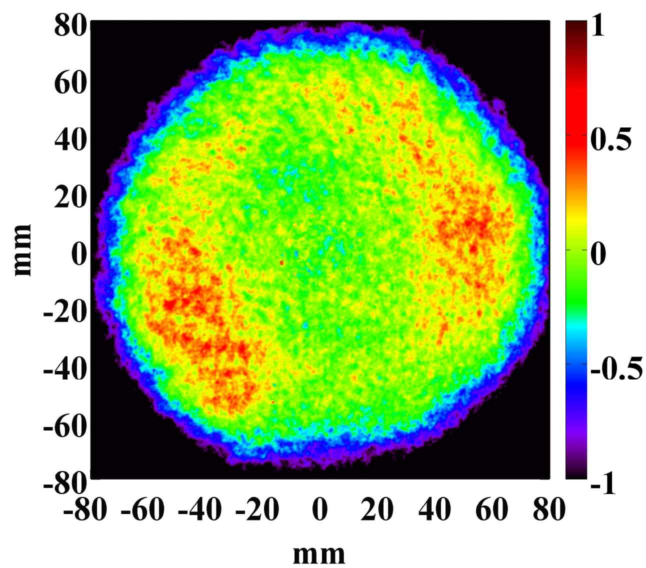

Fig. 1. (left) Pictures of an Advanced LIGO mirror supported by a pendulum suspension. (right) phase map of a polished, but uncoated mirror.

2. The LIGO Mirrors

After an initial phase of commissioning and observation, the initial LIGO interferometers [1] are being upgraded in multifarious ways, with the new Observatory referred to as Advanced LIGO [2]. The new interferometer will be fed with a 200 W CW Nd:YAG laser [3] which will be resonantly built up to produce a circulating power of $\simeq$ 800 kW in the 4 km Fabry-Perot cavities which comprise the Michelson interferometer arms. The Fabry-Perot cavity mirrors are made of low absorption fused silica (Heraeus Suprasil 311 for the end mirrors and ultra-low absorption Heraeus Suprasil 3001). These 40 kg mirrors have a diameter of 34.5 cm and a thickness of 20 cm.

3. Absorption

The absorption in the bulk substrates and on the high reflection coatings of the cavity mirrors is small enough to not be a significant contributor to the overall power budget of the interferometers. Nonetheless, these sources of absorption lead to deleterious wavefront distortions on the light through thermal expansion of the cavities' high reflection faces and thermo-refraction (dn/dT of fused silica) in the bulk of the input coupling mirrors. These thermal distortions reduce the contrast achievable at the Michelson dark port [4] and disturb the error signals in the interferometric global alignment control system [5]. The Suprasil 3001 substrates have an absorption of < 0.5 ppm/cm and the high reflection coatings (applied by the Laboratory for Advanced Materials in Lyon) have an absorption of 0.4 ± 0.2 ppm per reflection.

4. Scattered Light

Light which is scattered out of the fundamental TEM00 mode of the Fabry-Perot cavities reduces the sensitivity in many ways: the reduced buildup reduced the overall signal strength, the scattered light may scatter back into the interferometer after interacting with the vacuum system and introduce phase noise on the light, and the losses degrade the entanglement of photons in non-classical states of light which can be used to enhance the interferometer performance [6].

References

1. B. P. Abbott, R. Abbott, R. Adhikari, and et al., "LIGO: the laser interferometer Gravitational-Wave observatory," Reports on Progress in Physics **72**, 076,901+ (2009).
2. G. M. Harry, "Advanced LIGO: the next generation of gravitational wave detectors," Classical and Quantum Gravity **27**, 084,006 (2010).
3. B. Willke, K. Danzmann, M. Frede, P. King, D. Kracht, P. Kwee, O. Puncken, R. L. Savage, Jr., B. Schulz, F. Seifert, C. Veltkamp, S. Wagner, P. Weßels, and L. Winkelmann, "Stabilized lasers for advanced gravitational wave detectors," Classical and Quantum Gravity **25**, 114,040 (2008).
4. T. T. Fricke, N. D. Smith-Lefebvre, R. Abbott, R. Adhikari, K. L. Dooley, M. Evans, P. Fritschel, V. V. Frolov, K. Kawabe, J. S. Kissel, B. J. J. Slagmolen, and S. J. Waldman, "DC readout experiment in Enhanced LIGO," Classical and Quantum Gravity **29**, 065,005 (2012).
5. K. L. Dooley, L. Barsotti, R. X. Adhikari, M. Evans, T. T. Fricke, P. Fritschel, V. Frolov, K. Kawabe, and N. Smith-Lefebvre, "Angular control of optical cavities in a radiation-pressure-dominated regime: the Enhanced LIGO case," Journal of the Optical Society of America A **30**, 2618 (2013).
6. H. Miao, H. Yang, R. X. Adhikari, and Y. Chen, "Quantum limits of interferometer topologies for gravitational radiation detection," arXiv preprint arXiv:1305.3957 (2013).